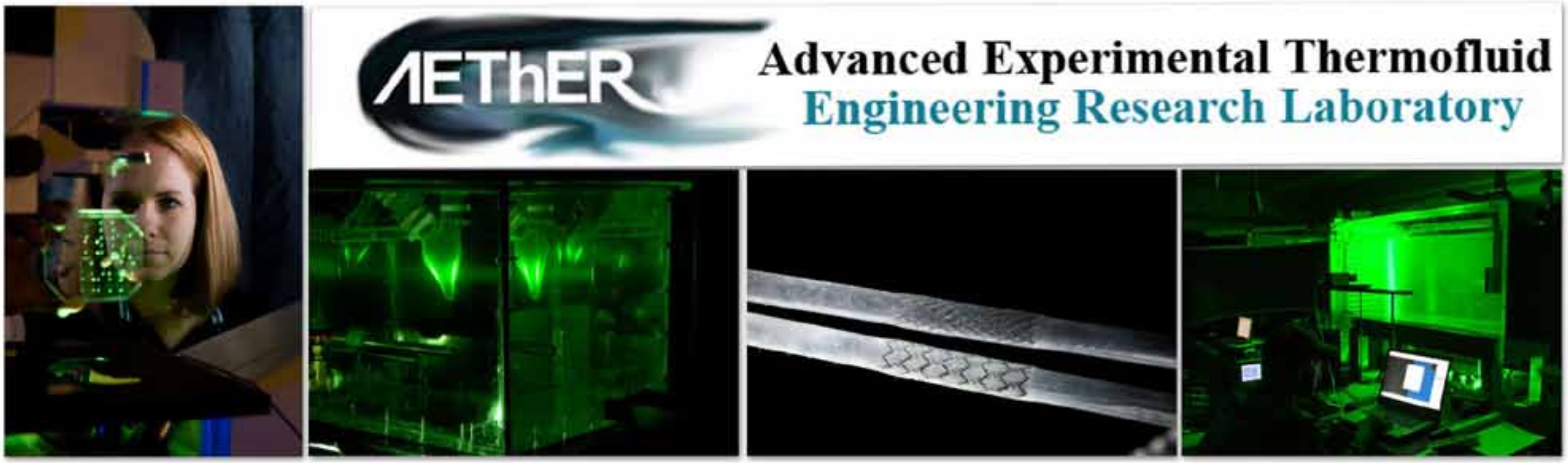


Fluid Mechanics of Arterial Stents and Left-Ventricular Diastolic Dysfunction

Pavlos P. Vlachos, PhD

Associate Professor

Department of Mechanical Engineering

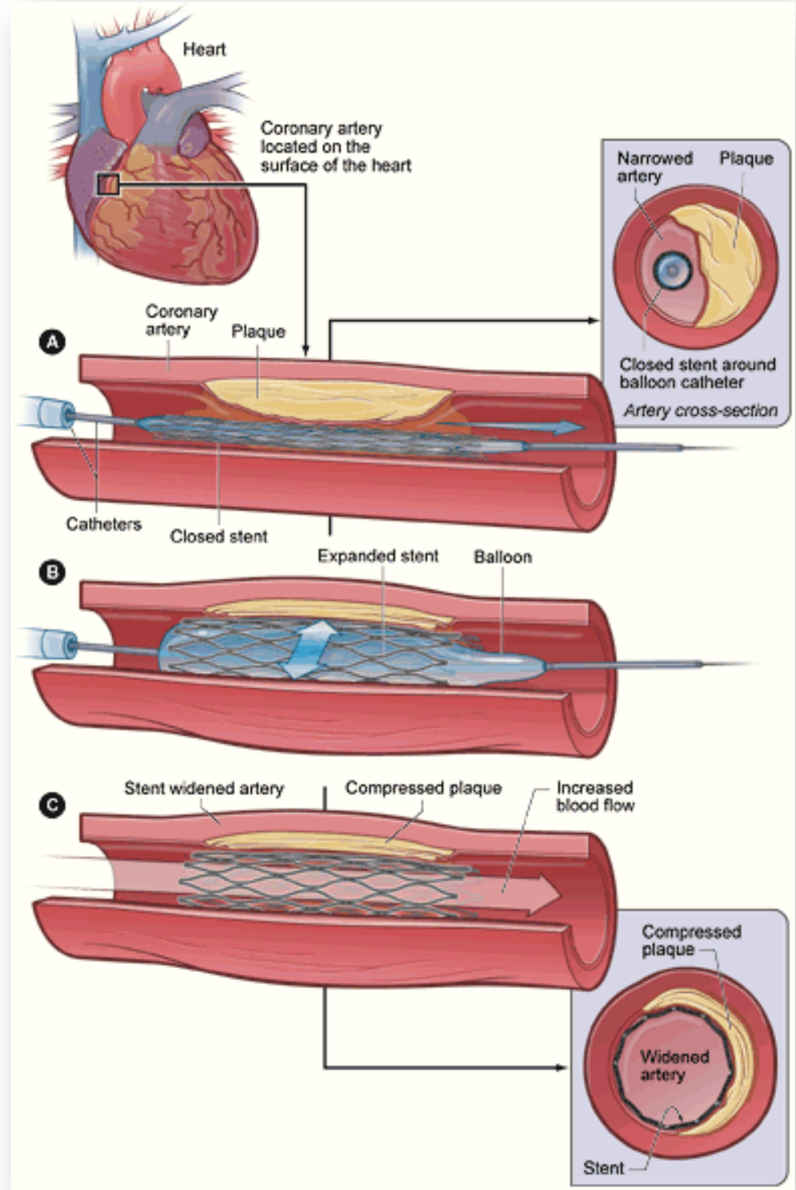
School of Biomedical Engineering and Sciences

Virginia Tech

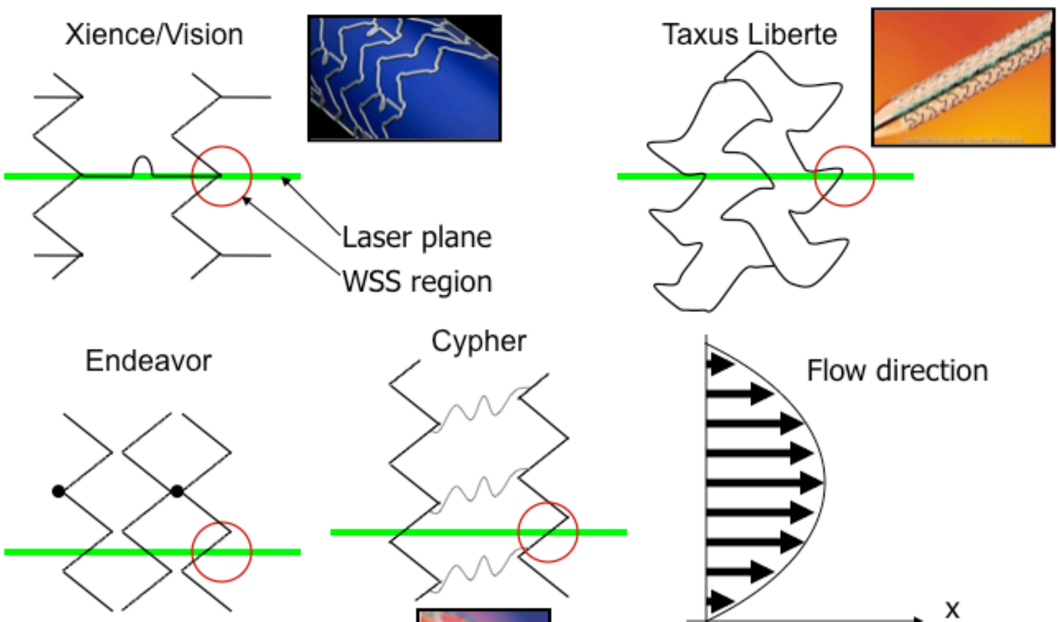
http://www.me.vt.edu/AEThER/index.html

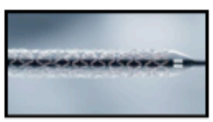
Stents are the #1 treatment for Coronary Artery Disease

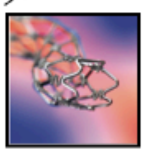
- Cardiovascular Diseases (CVD) are the leading cause of death in the US
    - Coronary Artery Disease (CAD) makes up 54% of these deaths
    - ~1 million people and $430 billion lost to CVD in every year
- Coronary Stents are among the most popular treatments for CAD
    - Over $6 billion/year market



Four commercial stents and four clinically relevant configurations were explored

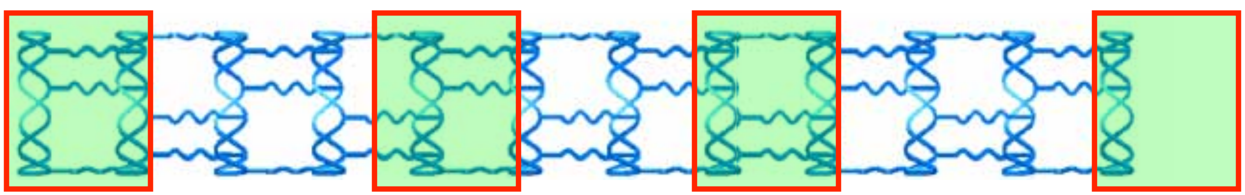




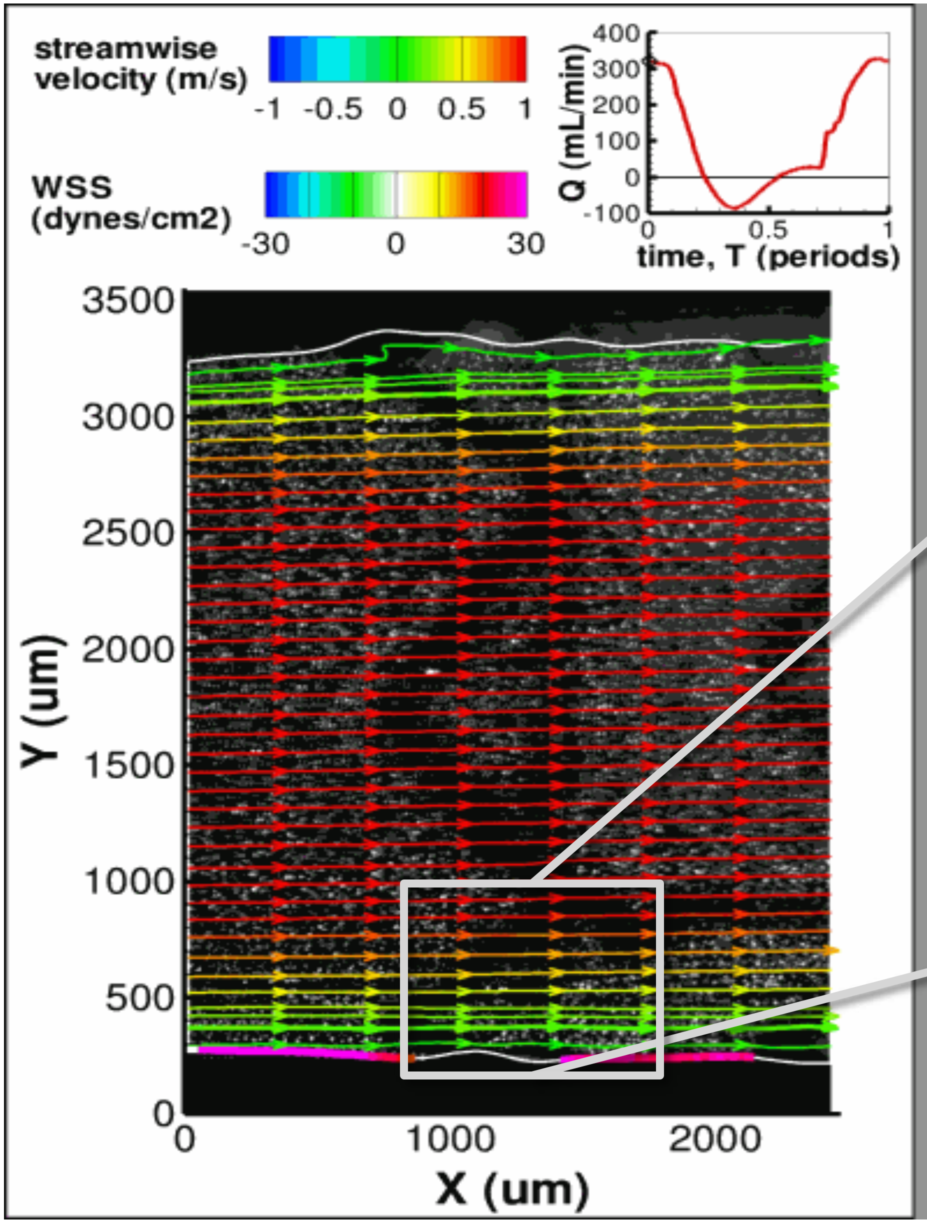


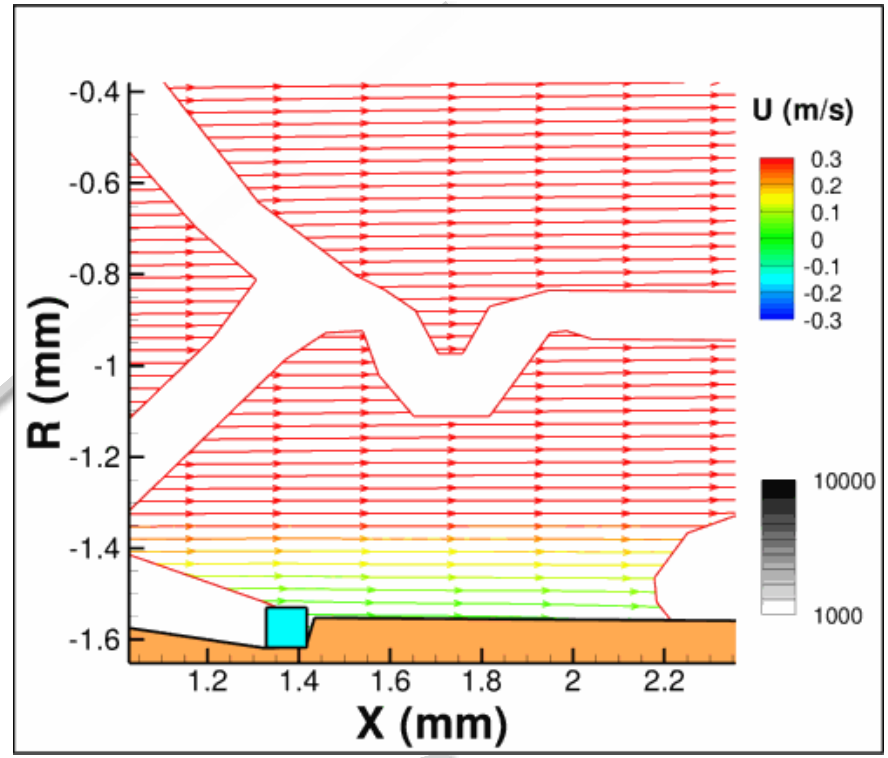
ROI were selected to create as much consistency between the different designs as possible

	Stent tested	Stent size (diameter x length)
Section 1	XIENCE™	3 mm x 18 mm
Effect of Stent Design	TAXUS® Liberte™	3 mm x 20 mm
	CoStar™	3 mm x 16mm
	Endeavor™	3 mm x 18 mm
	Cypher®	3 mm x 18 mm
Section 2 **Effect of Stent Length**	XIENCE™	3 mm x 28 mm
Section 3	XIENCE™	3 mm x 18 mm (3.75mm expansion)
Effect of Stent Diameter	XIENCE™	4 mm x 18 mm
Section 4 **Effect of Stent Overlap**	XIENCE™	3 mm x 18 mm (two stents, 4mm overlap)
Section 5 **Effect of Drug Coating**	VISION™	3 mm x 18 mm



Example: Abbott Xience 3x18 US Re=160

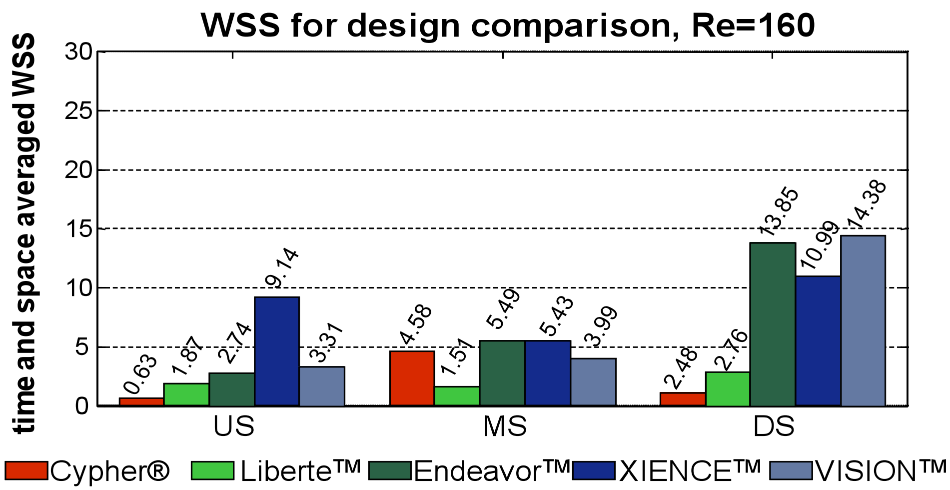


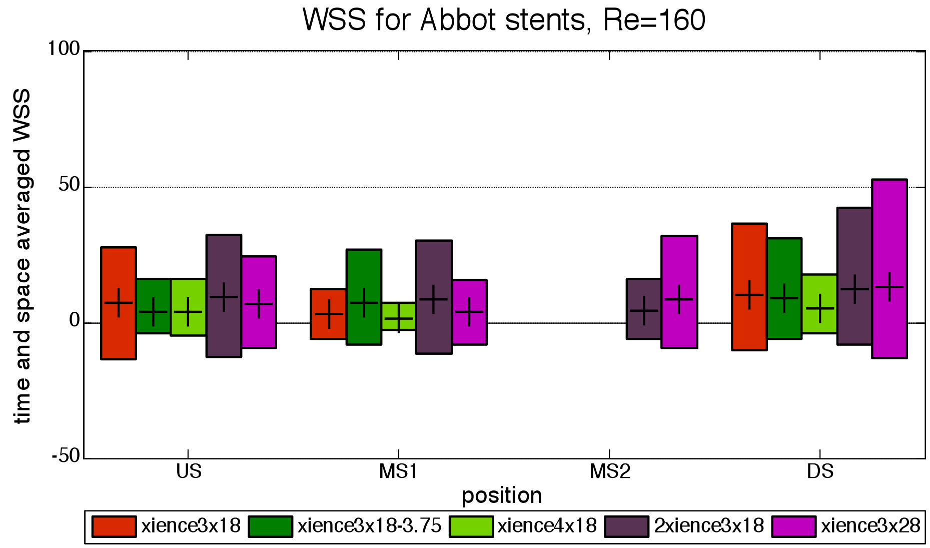


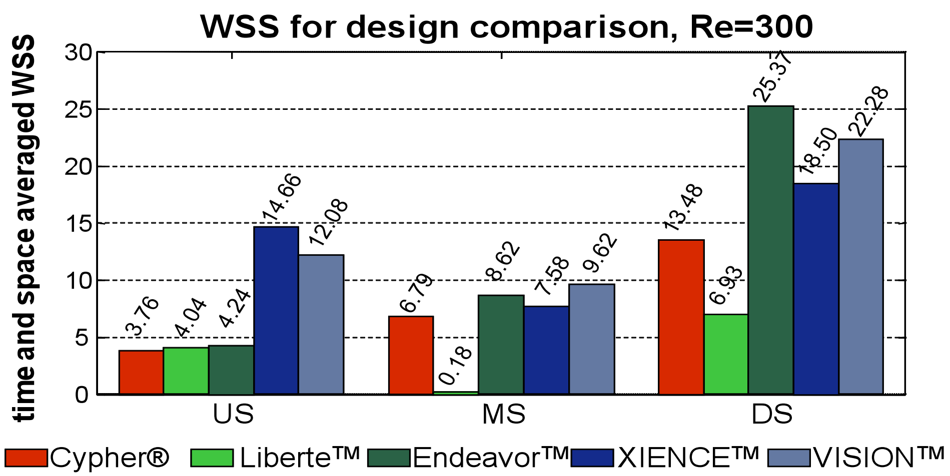
Coherent Structure/Vortex Identification using swirl-strength (λ_{ci}) method by:

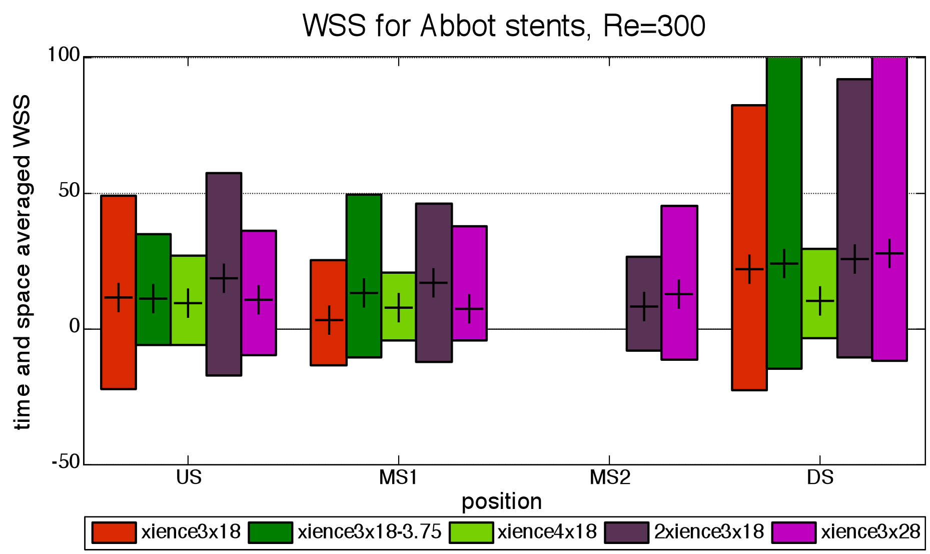
Zhou, J., R.J. Adrian, S. Balachandar, and T.M. Kendall. Mechanisms for Generating Coherent Packets of Hairpin Vortices in Channel Flow. *Journal of Fluid Mechanics*. 387:353-396, 1999.

Stent design and configuration have drastic effects on WSS

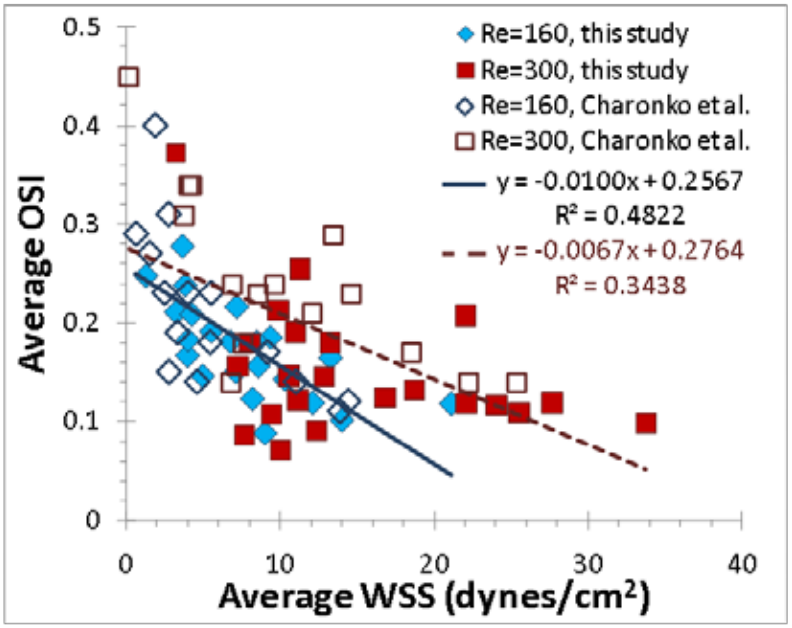








There is an inverse relationship between WSS and OSI; WSS correlates with in-vivo EC coverage data

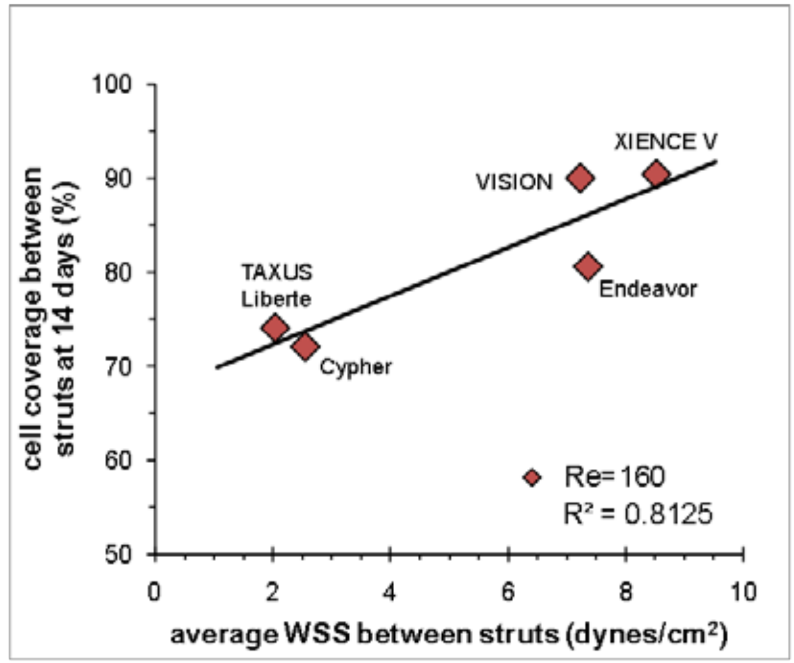


If instantaneous WSS merely scales with the average, OSI should remain constant

Instead, for an inverse relationship, either the peak WSS must become less positive, or the minimum more negative.

Either condition points to greater receptivity of flow at that location to fluctuations in the driving pressure gradients

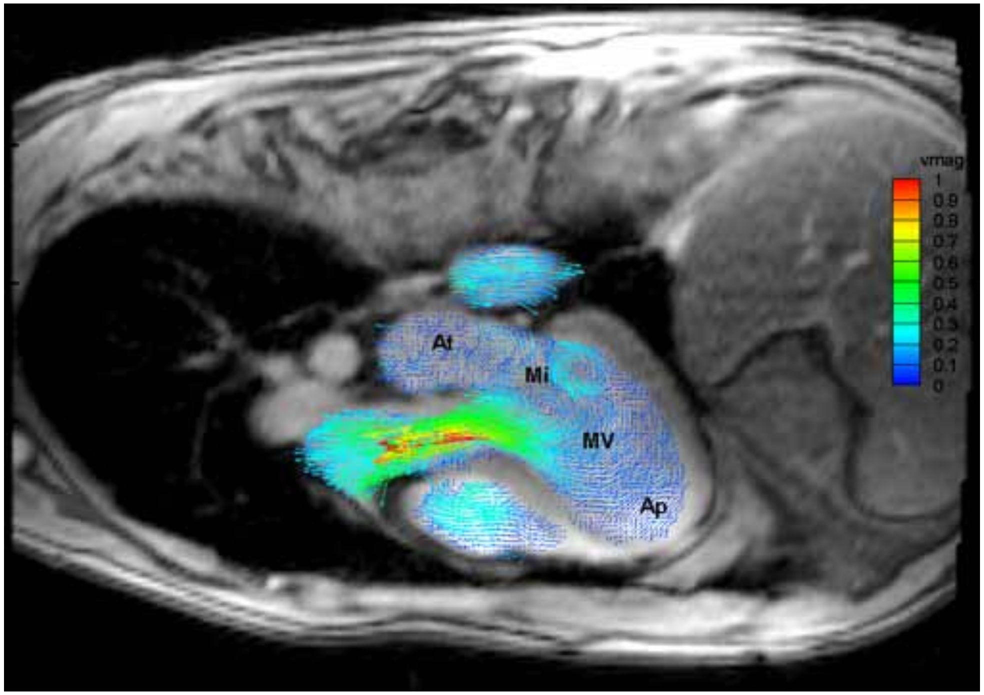
Joner, M., G. Nakazawa, A.V. Finn, S.C. Quee, et al. Endothelial Cell Recovery Between Comparator Polymer-Based Drug-Eluting Stents. *Journal of the American College of Cardiology. 52:333-342, 2008.*

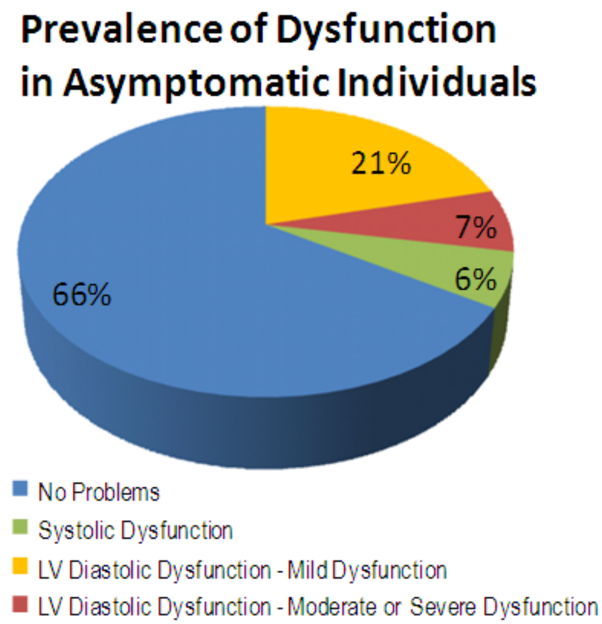


Strong correlation of the WSS with EC coverage is shown in comparisons with animal testing for the same set of commercial stent designs

John Charonko, Satyaprakash Karri, Jaime Schmieg, Santosh Prabhu, and Pavlos Vlachos, “In-Vitro, Time-Resolved PIV Comparison Of The Effect Of Stent Configuration”, **Annals of Biomedical Engineering Volume 38, Issue 3 (2010), Page 889**

John Charonko, Satyaprakash Karri, Jaime Schmieg, Santosh Prabhu, and Pavlos Vlachos, “In-Vitro, Time-Resolved PIV Comparison Of The Effect Of Stent Design On WSS” **Annals of Biomedical Engineering, 2009. 37(7): p. 1310-1321.**



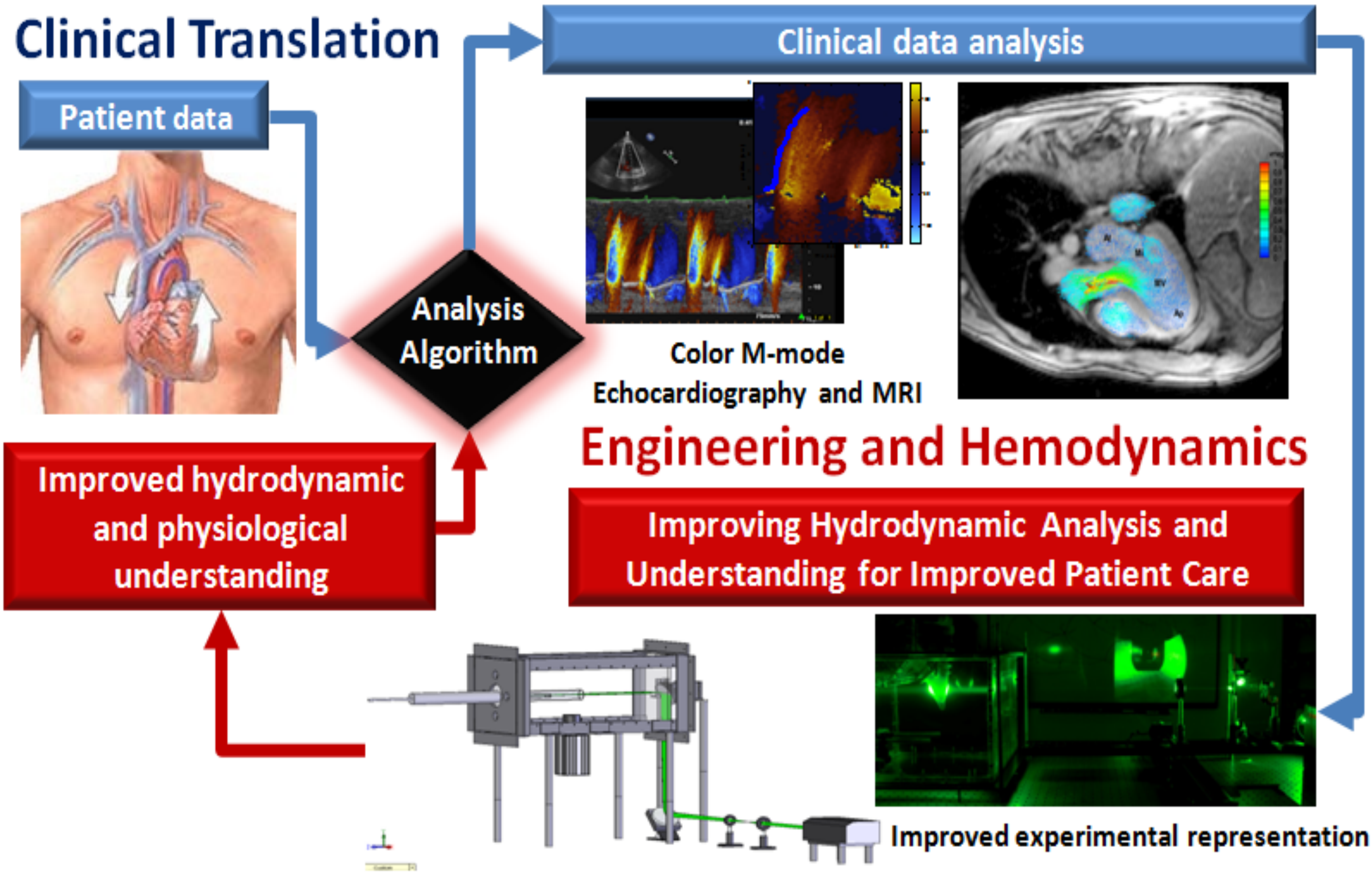


CARDIOVASCULAR FLUID MECHANICS OF LEFT-VENTRICULAR DIASTOLIC DYSFUNCTION

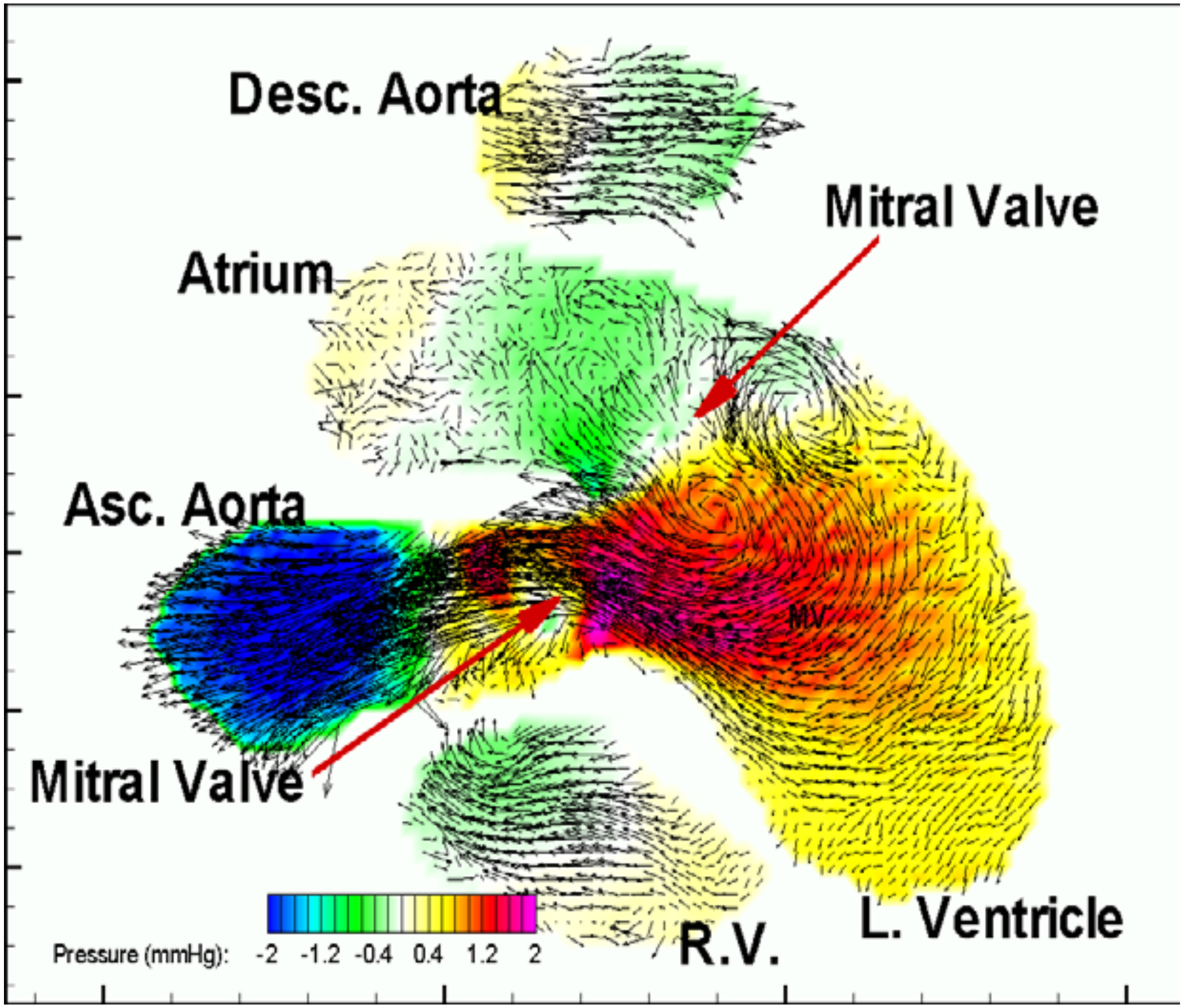
Rahul Kumar, John Charonko, W. Gregory Hundley, Craig A. Hamilton, Kelley C. Stewart, Gary R. McNeal, Pavlos P. Vlachos, William C. Little, “Assessment of Left Ventricular Diastolic Function Using Four-Dimensional Phase Contrast Cardiac Magnetic Resonance” **submitted to Journal of Cardiovascular Magnetic Resonance**

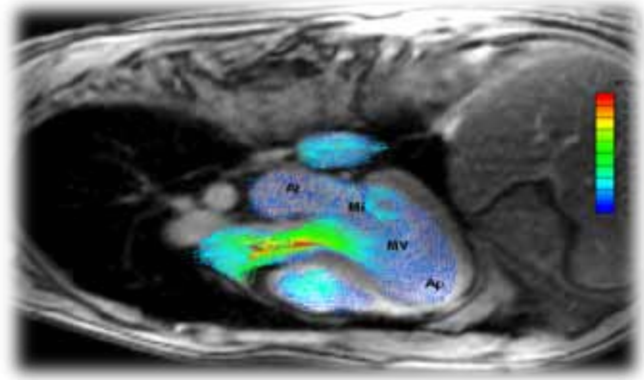
Stewart C. Kelley, Charonko J. John, Kumar Rahul, Vlachos P. Pavlos, Little C. William, “New Method of Evaluating Left Ventricular Diastolic Function from Color M-mode Echocardiography”. **submitted to Journal of the American College of Cardiology**

A Biomedical engineering framework for diagnosing heart Left Ventricular Diastolic Dysfunction (LVDD)



Next step: *Develop working hypothesis for the underlying fluid dynamics using MR Velocimetry*

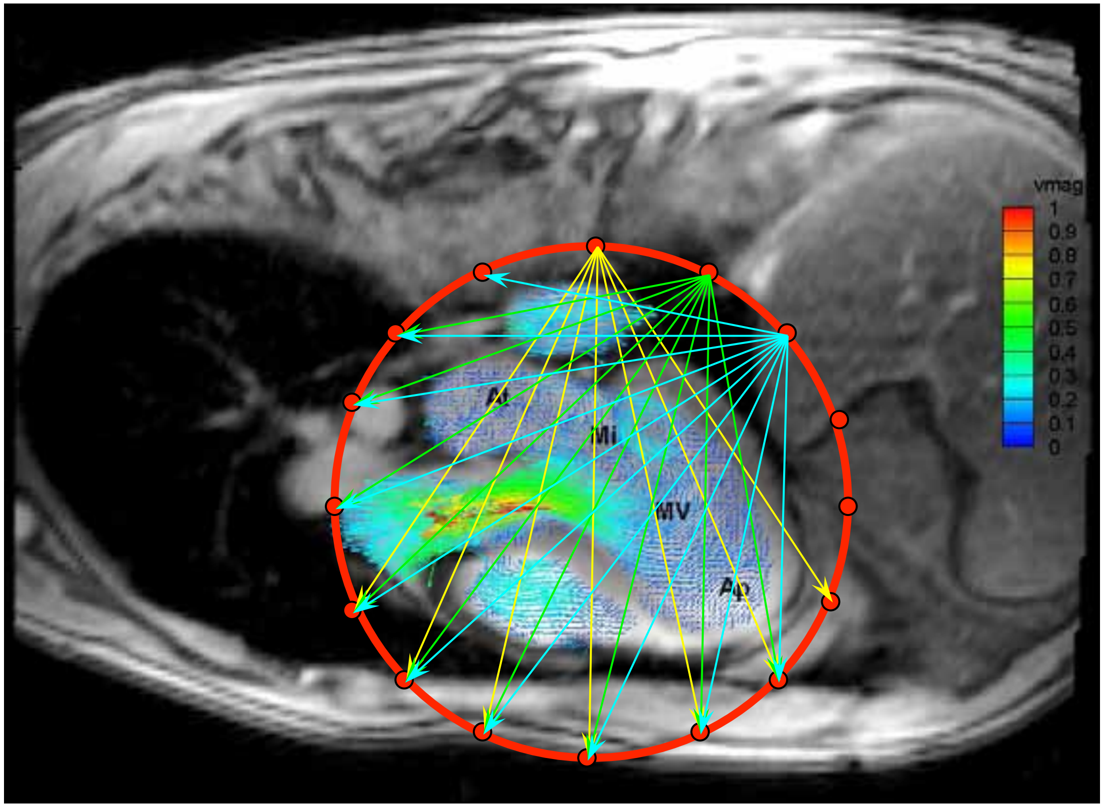




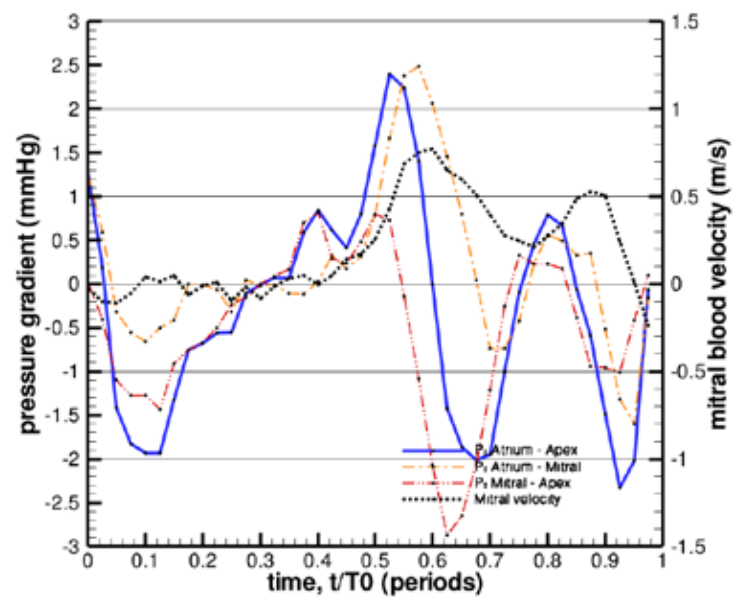
Vortex formation
vs.
Propagation length
vs.
Pressure gradients

Atrial "pushing"
vs.
Ventricular "pulling"

Pressure integration is preformed using omni-directional virtual boundary *



*Liu and Katz, 2006, "Instantaneous Pressure and Material Acceleration Measurements using a Four exposure PIV System," Exp. in Fluids, Vol. 41, pp. 227-240.

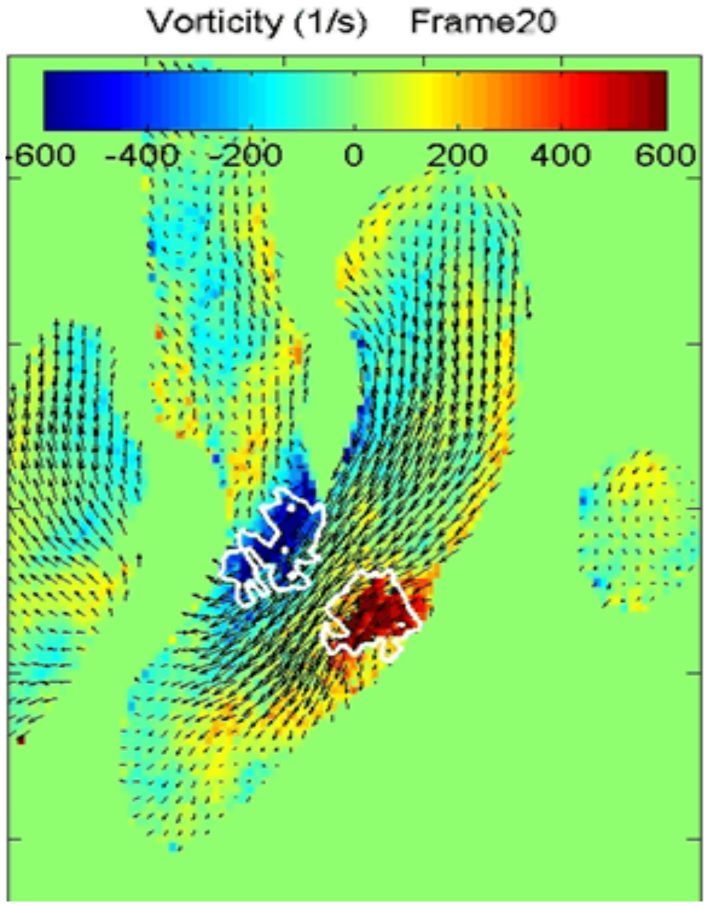


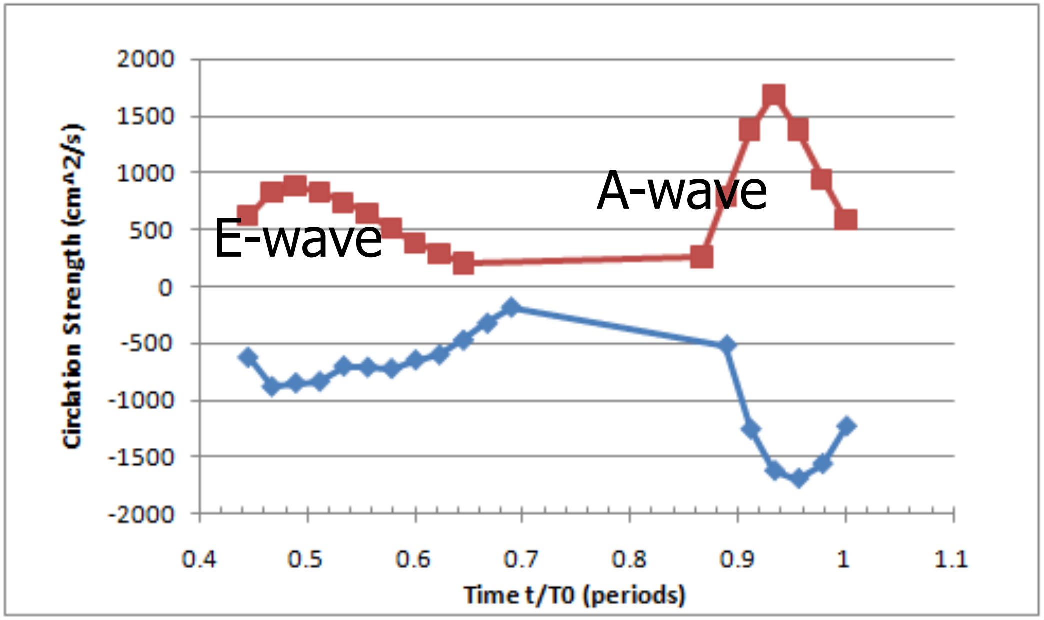
$$\nabla P = -\left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u}\right) + \frac{1}{\mathrm{Re}}\left(\nabla^2 \vec{u}\right)$$

Charonko et. al, "Assessment of Pressure Field Calculations from Spatiotemporally Resolved Particle Image Velocimetry Velocity Fields", **in review to Measurement Science and Instrumentation**

Flow field and vortex-circulation is determined using the pcMRI data

Using a vortex identification scheme we can track the location and strength of vortices within the left ventricle

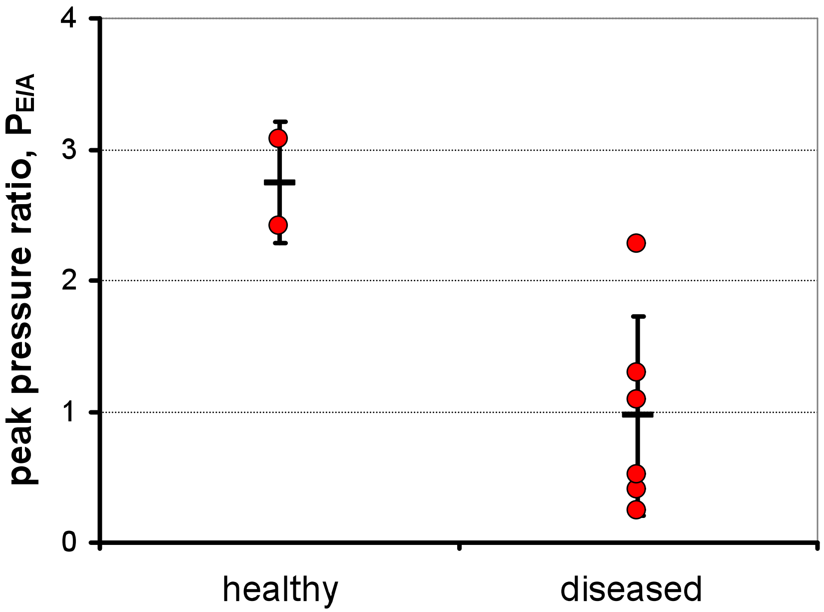




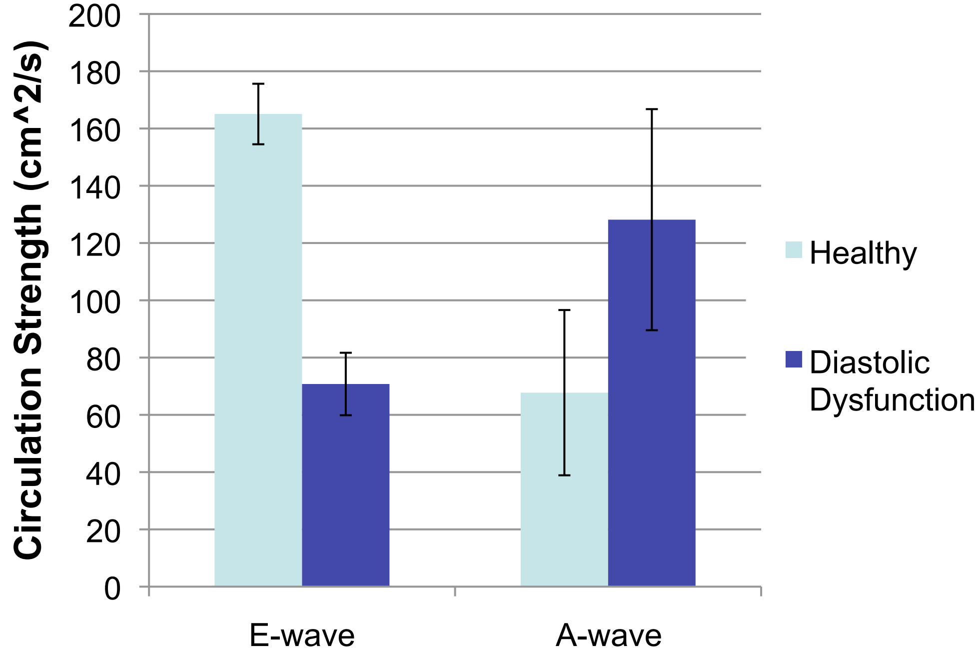
Calculate vorticity fields and circulation strength from pcMRI data

Atriogenic filling reverses the vortex formation characteristics

Comparison of peak pressure difference between healthy and diseased



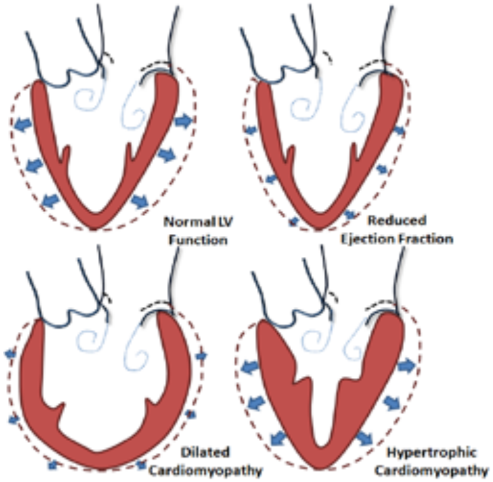
Comparison of E-wave and A-wave Circulation Strength for Healthy and Diseased patients

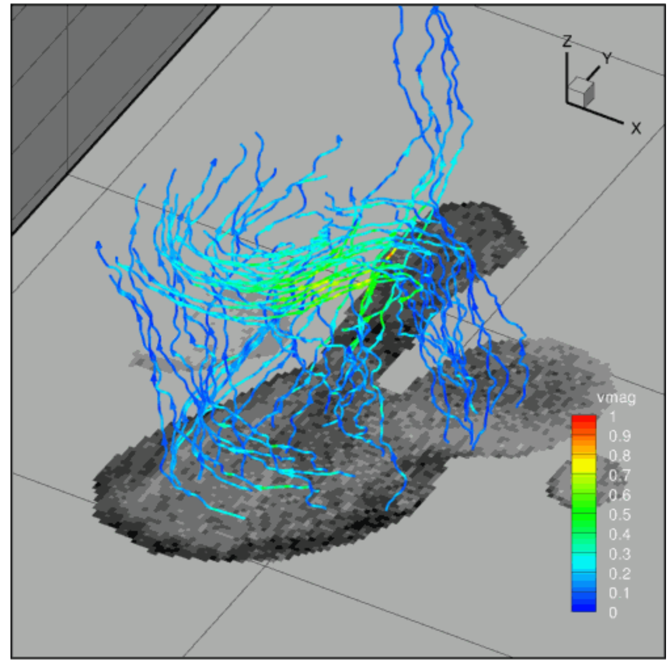


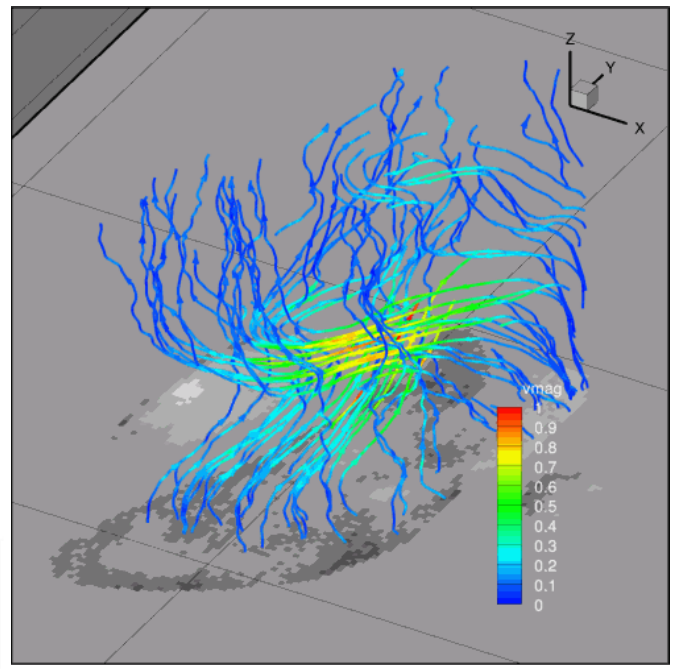
N=8 (2 Healthy and 6 Diastolic Dysfunction Patients)

Bars represent patient data range

The flow characteristics during LV filling can shed light on the mechanism of dysfunction







Differences exist in the filling patterns between healthy and diseased patients

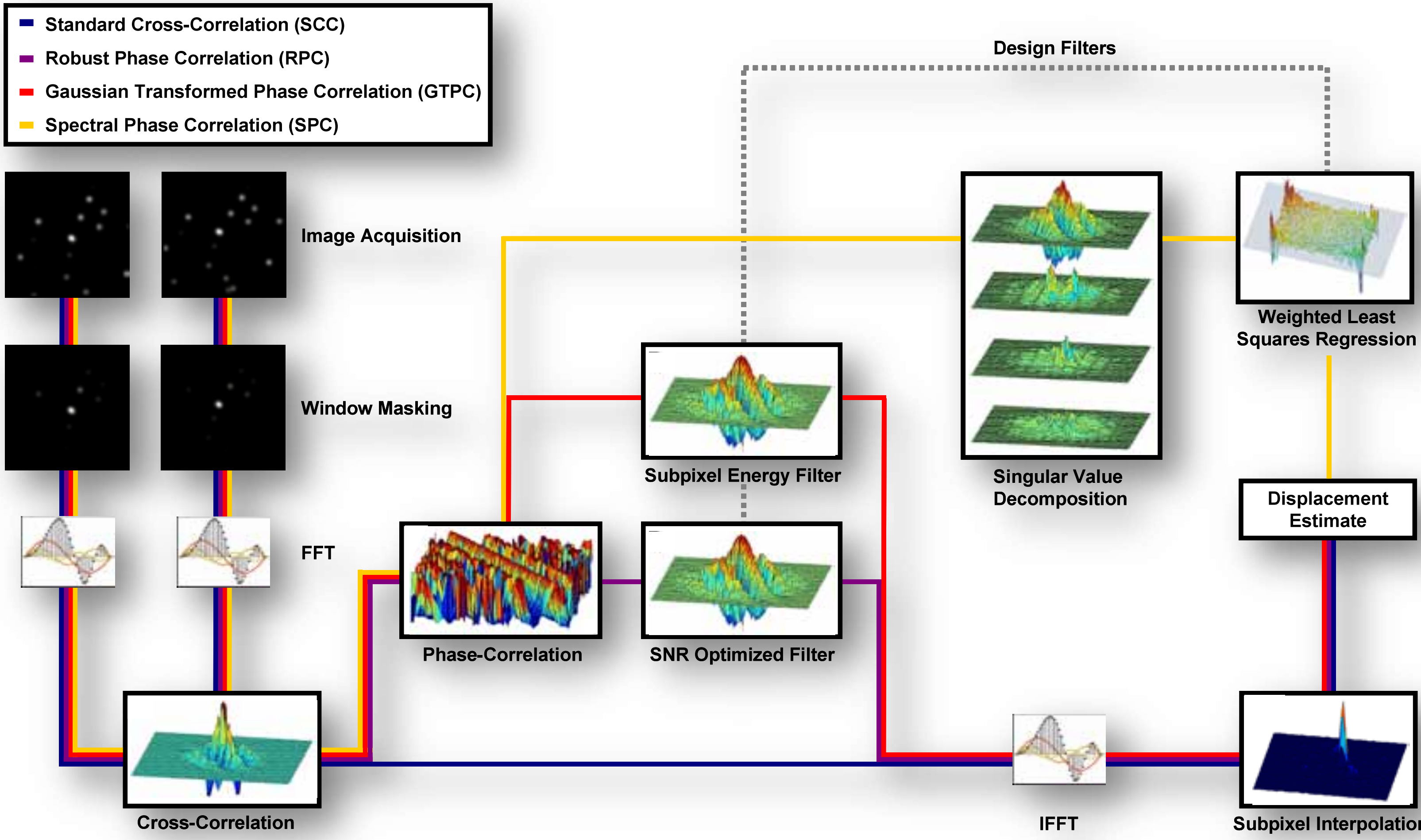
The flow structure (vortex formation) appears to correlate with the abrupt development of adverse pressure gradient in the LV

The initial filling wave flow characteristics strongly correlated and classify healthy vs. diseased

On that basis a “robust” and “objective” diagnostic framework is developed and a hypothesis for the relevant flow physics is proposed

Rahul Kumar, John Charonko, W. Gregory Hundley, Craig A. Hamilton, Kelley C. Stewart, Gary R. McNeal, Pavlos P. Vlachos, William C. Little, “Assessment of Left Ventricular Diastolic Function Using Four-Dimensional Phase Contrast Cardiac Magnetic Resonance” **submitted to Journal of Cardiovascular Magnetic Resonance**

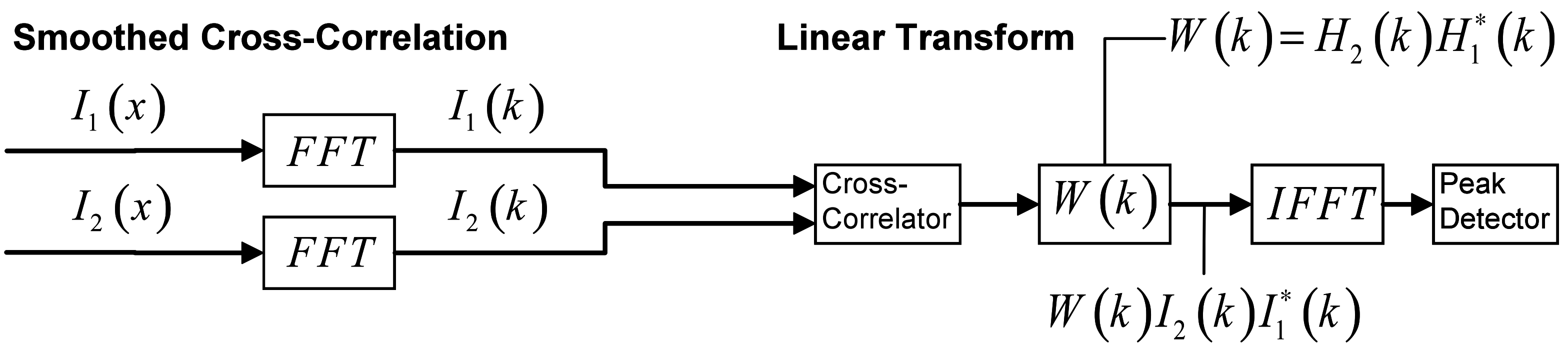
Novel DPIV Processing Methodology: Phase Correlation



These methods are designed to improve the estimation of the cross-correlation by applying a series of dynamic and analytical spectral filters

Eckstein, A. C., J. Charonko, and P.P. Vlachos (2008). "Phase correlation processing for DPIV measurements." Experiments in Fluids **45(3): 485-500.**
Eckstein, A. C. and P.P. Vlachos, "DPIV Robust Phase Correlation" Measurement Science and Technology
Eckstein, A. C. and P.P. Vlachos, "Assessment of Advanced Windowing Techniques for Digital Particle Image Velocimetry (DPIV)" Measurement Science and Technology

RPC is an evolution of the Generalized Cross Correlation



analytically constructed weighting function

$$\textbf{RPC Estimator} \quad = \frac{C_{21}(\vec{k}) \cdot W(\vec{k})}{\sqrt{C_{22}(\vec{k}) C_{11}(\vec{k})}} = C_{21}(\vec{k}) \underbrace{\frac{W(\vec{k})}{\sqrt{C_{22}(\vec{k}) C_{11}(\vec{k})}}} = W(\vec{k}) \exp\left(ik\phi(\vec{k})\right)$$

dynamic phase-transform filter

$$I_1(\vec{x}) = s_1(\vec{x}) + n_1(\vec{x})$$

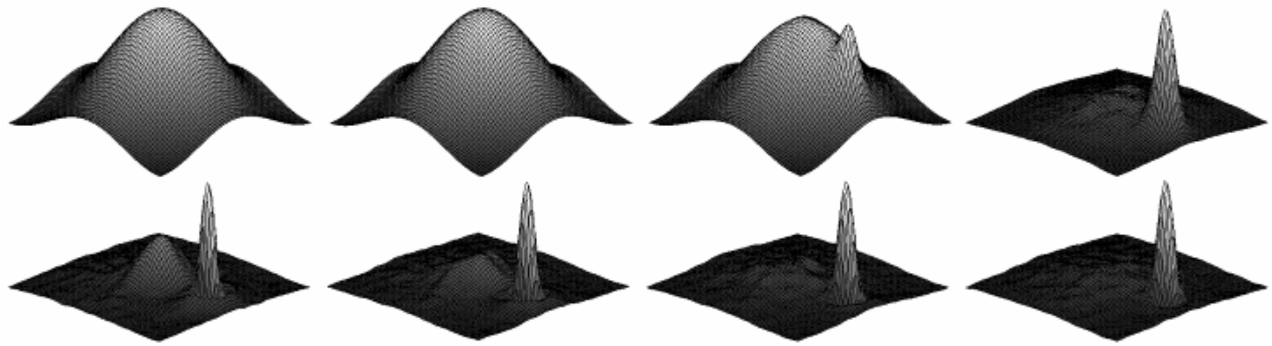
$$I_2(\vec{x}) = s_2\left(\vec{x} + \vec{D}\right) + n_2(\vec{x})$$

$$W(\vec{k}) = \frac{C_{s_1 s_2}(\vec{k})}{C_{n_1 n_2}(\vec{k})} = \frac{E_{PIP}}{E_{aliased} + \underbrace{E_{quantized} + E_{FFT} + E_{noise}}_{\text{random processes}}}$$

RPC provides a robust DPIV velocity estimation

Standard evaluation technique

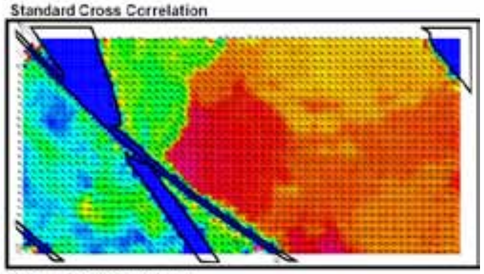
Filtered Phase Correlation



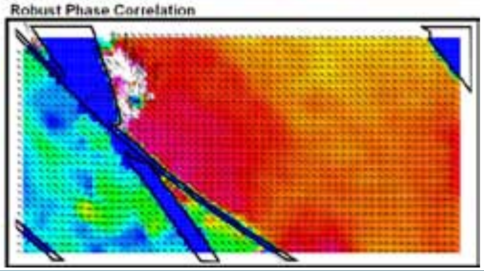
High background noise ← - - - - - - - - - - → Minimal background noise

2001 PIV Challenge Case C: Turbine Blade

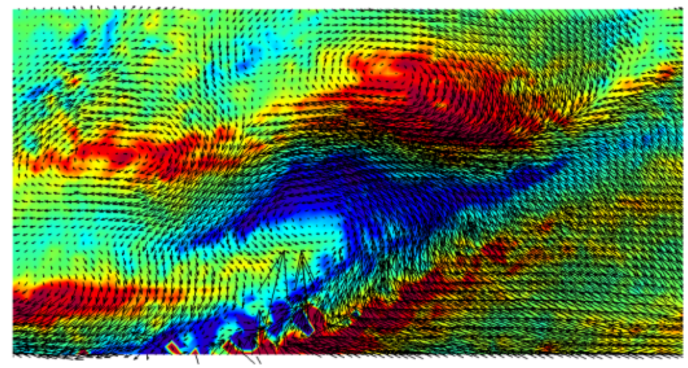
Standard Cross Correlation



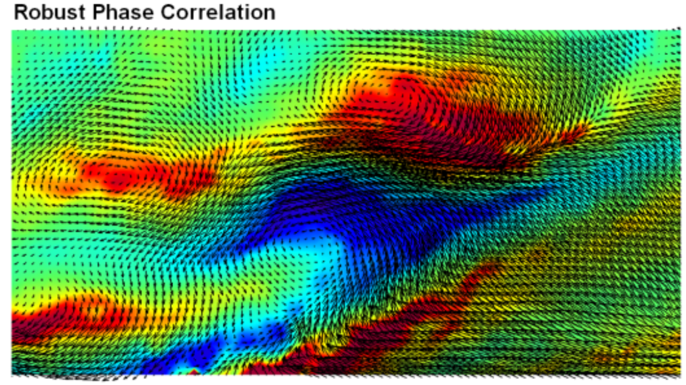
Robust Phase Correlation



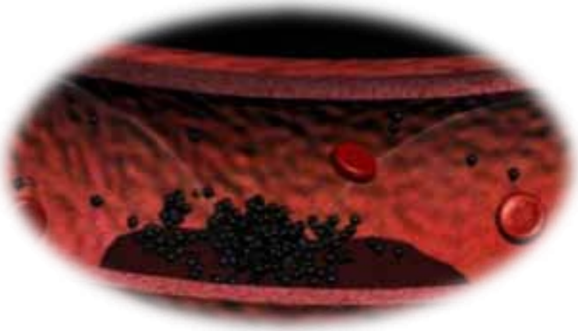
Standard Cross Correlation

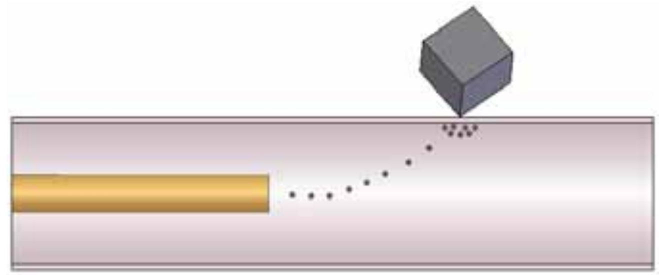


Robust Phase Correlation

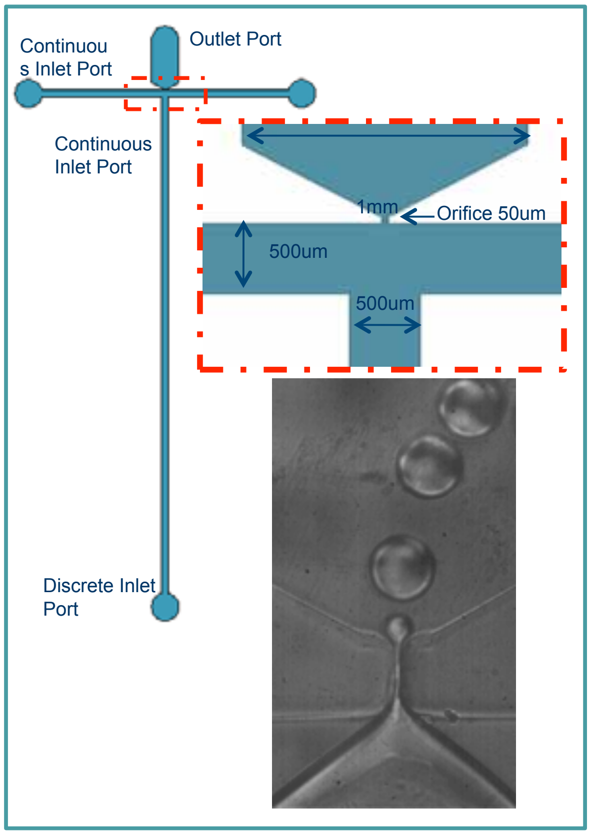


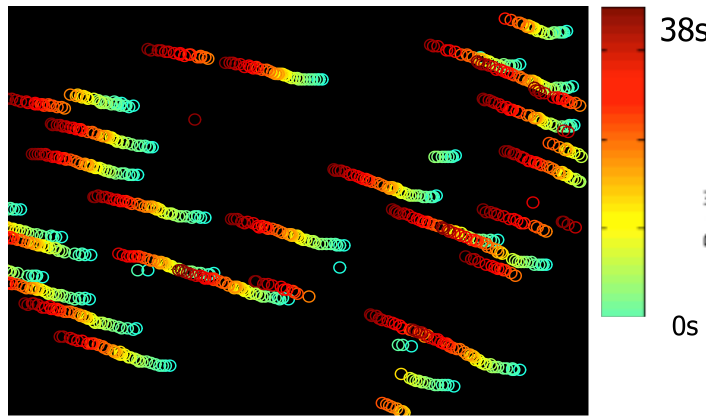
Drug Delivery, and Microscale Flows

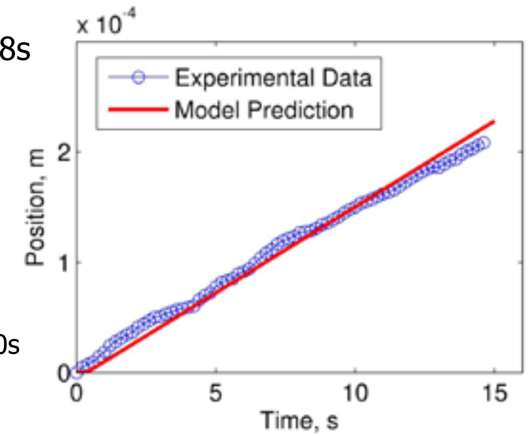


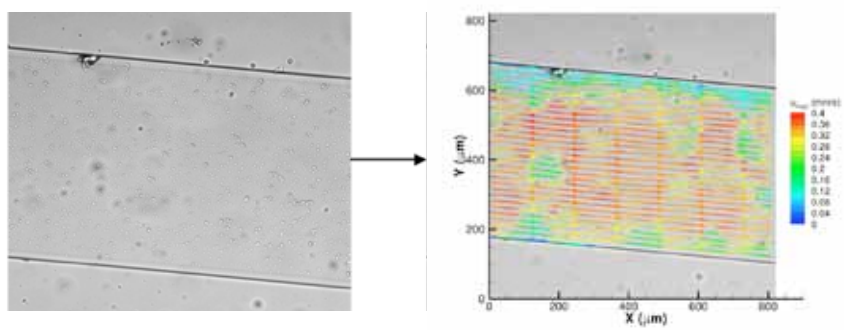


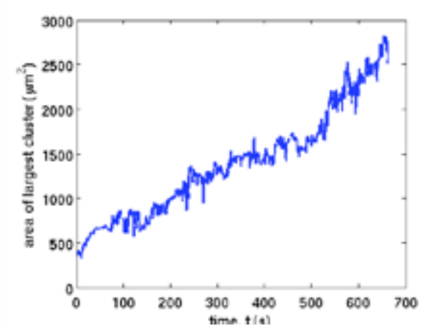
Development of magnetic micro-droplets











VirginiaTech